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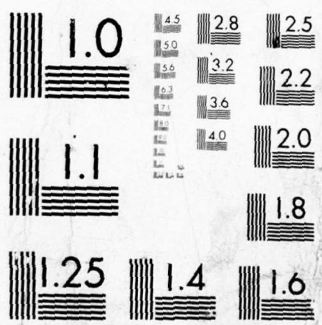

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Report TD75296

STUDY OF THERMAL INSULATING BLANKET CONSTRUCTIONS WITH REFLECTING LAYERS

Robert E. Wallace
Varo, Inc.
Texas Division
2201 W. Walnut St.
Garland, Texas 75040

April, 1980

Final Report

Distribution of this document is unlimited

Prepared for:

U. S. A. MERADCOM, ATTN: DRDME-RT (T. STECK)
Camouflage and Topographic Laboratory
Fort Belvoir, Virginia 22060

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER TD75296	2. GOVT ACCESSION NO. AD-A084 138	3. RECIPIENT'S CATALOG NUMBER 9
4. TITLE (and Subtitle) 6 STUDY OF THERMAL INSULATING BLANKET CONSTRUCTIONS WITH REFLECTING LAYERS.		5. TYPE OF REPORT & PERIOD COVERED Final rept.
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) 10 Robert E. Wallace		8. CONTRACT OR GRANT NUMBER(s) 15 DAAK70-79-C-0041
9. PERFORMING ORGANIZATION NAME AND ADDRESS Varo, Inc., Texas Division 2201 W. Walnut St. Garland, Texas 75040		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS A0R04D61651
11. CONTROLLING OFFICE NAME AND ADDRESS USA MERADCOM ATTN: DRDME-RT (T.STECK) Camouflage and Topographic Laboratory Fort Belvoir, Virginia 22060	11	12. REPORT DATE Apr[redacted]980
		13. NUMBER OF PAGES 62
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) 12 61		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

14 TD-75296

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

DISTRIBUTION OF THIS ABSTRACT IS UNLIMITED

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Insulation
Reflective
Thermal
Camouflage
Infrared

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This study examines thermal insulating blanket constructions with reflecting layers theoretically. Twelve blanket designs were developed using primary criteria of insulating performance, flexibility and flame resistance. Designs were selected and prepared in sample size based on predicted insulating performance and material availability. These were furnished to MERADCOM for tests and evaluation.

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SUMMARY

The purpose of this blanket study was to investigate heat transfer within insulations, concentrating on the effect of reflecting layers, to survey and select suitable materials, and then to develop blanket designs with reflecting elements. It was anticipated that some of these would prove to be superior to the blanket used formerly in the Generator Exhaust Signature Suppression (GESS) system (a polyproplyene closed cell foam in a ripstop nylon jacket). In particular improved flame resistance was desired. Other important considerations in blanket design were R-factor (resistance to heat transfer), flexibility, bulk and weight.

Twelve designs for blankets with reflecting layers were developed combining various component layers so that the overall R-factor for the sandwich would meet or exceed that for the baseline GESS blanket with polyproplene foam insulation. Component layer R-factors were calculated using mathematical models for heat transfer developed in the beginning of the study.

Blanket swatches were prepared for selected blanket designs at the end of the study with the dual criteria of blanket performance and material availability. These were supplied to MERADCOM for their evaluation.

This study concluded that reflective elements should improve blanket insulating effectiveness. In fact, totally reflective blanket systems appear to provide the best insulation (highest R-factor for the thickness) although their ruggedness is uncertain.

Design number 11 in the blanket designs matrix (Figure 11), with all reflective insulation appears at this time to be the optimum design of the candidates considered. It would best be formed with metalized Kapton film inside a chloroprene coated Kevlar fabric jacket.

It should be noted that this study deals with only the above mentioned performance criteria and does not address the problem of day solar loading effects which were not within the scope of this contract.

PREFACE

Work performed in this study was authorized under Contract DAAK70-79-C-0041 from the Mobility Equipment Research and Development Command (MERADCOM) at Fort Belvoir, Virginia. The study was intended to suggest improvements in construction which might be made in future blankets used as part of thermal camouflage systems.

The author wishes to acknowledge his appreciation for technical guidance during the course of this study which was provided by Mr. Tom Steck of MERADCOM.

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1.0 INTRODUCTION

It was the intent of this work to examine heat transfer in insulations, especially so that the effect of reflective layers could be evaluated regarding resistance to thermal transference, and create combinations of insulating layers including reflectors, to form candidate thermal blanket designs. A parallel effort was to find materials suitable for use in these designs. Candidate blanket designs were generated by adding R-factors for various component layers trying to attain a total R-factor as good as or better than that for a baseline blanket formed of three layers of nominally 1/4 inch thick polypropylene closed cell foam. Its thermal resistance was taken to be the standard level to meet or exceed.

The final step in performance of work on this contract was construction of sample blankets of selected designs. The selection process for designs was based on flammability, weight, thickness, flexibility and thermal transference resistance (R-factor), and on material availability.

The scope of work can be summarized as theoretical analysis looking into the heat transfer processes between reflecting layers, a material survey for

materials (discrete insulation, reflector layer film and separator, jacket fabric and jacket elastomer coating), blanket designing, and finally actual construction of sample blankets from selected available materials.

2.0 INVESTIGATION

2.1 Material Survey

2.1.1 Method

Potential blanket materials were surveyed as part of the contract effort trying to find materials for optimum performance. Generally factors which were given greatest weight were flame resistance, operation at temperatures up to 250F, and flexibility. For component materials aimed at specific functions in the blanket structure more tailored performance factors were considered. For example, the coated fabric needs to be most resistant to flame and weathering exposure. Internal parts do not need to meet weathering criteria.

The method of attacking the evaluation of materials was to classify them according to one of five groupings related to performance within the blanket. These groupings were each considered with the factors which affect performance of that group function, assigning values from manufacturers' data and references in matrix form.

Thus, there are five matrices which lay out the performance of each material candidate according to its intended use. They are:

Discrete Insulation (foam, felt, special formulations), Figure 1

Jacket Fibers, Figure 2

Elastomer Coatings (to apply to jacket cloth), Figure 3

Films for Metalizing, Figure 4

Separator Materials, Figure 5

The metalized films and separator materials are examined looking for materials suited to the type of reflective barrier which is the special consideration of this report - two parallel reflector films with a separator material between.

2.1.2 Discrete Insulation

In Figure 1, the insulation candidates are presented. It may be seen that the two candidates which show best performance regarding flammability and resistance to heat are Johns Manville Min-K and Lockheed LI 900. Min-K in particular also has the lowest thermal conductivity of all candidates considered. Both have, however, flaws in other areas which make them unacceptable for the blanket application.

Min-K is destroyed by a water soak. Since that was regarded as a likely occurrence (precipitation entering through a tear in the jacket), and it is a very expensive material, Min-K was not pursued. The LI-900 material has the fatal flaw of being brittle. It is a rigid ceramic which is unsuited for the flexible application of the blanket.

	"PYRELL" POLYESTER/ POLYURETHANE	"MICROFOAM" CLOSE[D] CELL POLYPROPYLENE
CONTINUOUS USE TEMPERATURE	220F	250F
FLAMMABILITY	UL94-HF-1*[1] UL94 SE-1*	LOI 17.5 UL94-HF-1*[1] FLAMM[ABILITY] RESISTANCE GREATLY IMPR[OVED] WITH INTUMESCENT PAINT [ON] BOTH SIDES. UL94-HF-1 UNC[OATED]
FLEXIBILITY	GOOD -40F	-320F TO 250F REMAINS FLEXIBLE
ELONGATION		50-100%
THERMAL CONDUCTIVITY	$.25 \frac{\text{BTU in}}{\text{hrft}^2\text{F}}$ $(.036 \frac{\text{W}}{\text{m}^\circ\text{C}})$	$.27 \frac{\text{BTU in}}{\text{hrft}^2\text{F}}$ $(.039 \frac{\text{W}}{\text{m}^\circ\text{C}})$
DENSITY	2 - 4 lb/ft^3	0.7 lb/ft^3
COMPRESSION SET % (LOSS IN THICKNESS AFTER COMPRESSION)	8(2pcf) 12(4pcf)	10
AVAILABLE IN DARK COLOR	YES-NATURAL CHARCOAL (ALSO W FOIL FACE ½ mil PLASTIC)	WHITE ONLY
RESISTANCE TO WATER	GOOD*[2]	GOOD
WATER ABSORPTION	VERY HIGH	LOW
RESISTANCE TO OILS-GREASES	GOOD-CONDUCTIVITY AFFECTED IF WET	GOOD
COST	$20/$\text{ft}^3$ ($35/$\text{ft}^3$ with REFL FILM) (.29/ft^2 ¼THICK)	$3 - $4/$\text{ft}^3$ (W/O PAINT)

*IT IS POSSIBLE IN SOME CASES FOR AN ION EXCHANGE TO TAKE PLACE WHEN PYRELL IS IMMERSED IN WATER CONTAINING CERTAIN SOLUBLE MATERIALS. THIS EXCHANGE COULD CAUSE A REDUCTION IN FIRE-RETARDANT PROPERTIES.

*[1] GUIDE TO PLASTICS '78 PROPERTY & SPECIFICATION CHARTS McGRAW HILL, NY. 1977

*[2] POLYESTER/URETHANE FOAM DEGRA[DES] COMBINED HIGH TEMPERATURES AND H[IGH] HUMIDITY. ESTIMATED LIFE AT 215F A[ND] 70% HUMIDITY IS 3-6 MONTHS

	KEVLAR FELT	FLEXIBLE MIN-K	LOCKHEED LI-900
	400F	500F	2000 -2500F
LITY ED AT ED	INHERENTLY FLAME RESISTANT-SELF EXTINGUISHING	NON-FLAMMABLE	NON-FLAMMABLE
	GOOD -50F	MADE IN BLANKET FORM-FAIR DAMAGED BY CREASING FOLDS	RIGID CERAMIC-MAY SUFFER VIBRATION DAMAGE
	ABOUT SAME AS FIBERGLASS IN SAME BULK $\approx .035 \frac{w}{m^\circ C}$)	$.016 \frac{BTU}{hrftF}$ (100F MEAN) ($.028 \frac{w}{m^\circ C}$)	———
	3.5 up to 8 lb/ft^3 $\approx$ .6 x FIBERGLASS DENSITY	8 lb/ft^3 (LIGHT-WEIGHT)	9 lb/ft^3
	10	PROBABLY POOR	CRUSHES (100%)
	YELLOW ONLY-CANNOT BE DYED	———	———
	GOOD VERY HIGH	WATER SOAK DESTROYS VERY HIGH	——— ———
	GOOD-CONDUCTIVITY AFFECT IF WET	NOT-ATTACKED BUT WILL AFFECT THERMAL CONDUCTIVITY	GOOD-CONDUCTIVITY AFFECTED IF WET
	\$93/ft^3 (¼" felt)	\$10.25/FT^2 (3/8") \$7.25/ft^2 (1/8) \$330 to \$700/ft^3	\$500 - 600/ft^3
	THERE MAY BE BLUNT BALLISTIC PROTECTION AFFORDED WITH KELVAR FELT	EXCLUDED-WATER	EXCLUDED-BRITTLE

AT

Figure 1. Discrete Insulation

2

Of the remaining three materials Kevlar felt may be the most promising insulation candidate because of its temperature resistance, non-flammability and the side benefit of possible blunt ballistic protection which it may afford. It is said by the fiber manufacturer to have about the same thermal conductivity as fiberglass insulation in the same bulk, but since Kevlar is less dense, the Kevlar felt should weigh only about 60% of a fiberglass batt of the same bulk.

2.1.3 Jacket Fibers

Figure 2 depicts jacket fiber candidates and their performance according to the factors in the left hand column. Glass has excellent qualities except in one important area - flexibility. Since this factor is so important, glass fabrics are excluded on this basis. Polyester and nylon are good with the exception of flammability. If it were not for the potential of rectifying that with the elastomer coating, that would be sufficient to remove these candidates from further consideration. In the discussion of elastomer coatings, further reference will be made to the combined performance of the coating/fabric system.

Nomex and Kevlar fibers are very similar in performance and in fact, in makeup. Both are aramids. Kevlar is perhaps the better choice based on strength and the potential for some ballistic protection. Consequently, Kevlar fabric would appear to be the optimum choice apart from cost considerations.

	"NOMEX"–DUPONT ARAMID	"KEVLAR" 29 DUPONT ARAMID
RESISTANCE TO HEAT	350F (3000 HRS ~ 90% STRENGTH)	400F
FLAMMABILITY	LOI 29-30 NO MELT, SELF EXTINGUISHING	SELF-EXTINGUISHING NO MELTING-SIMILAR TO NOMEX
RESISTANCE TO COLD °F	CRYOGENIC	-50F *1
ELONGATION, %	MEDIUM *4	4 *1
FLEXIBILITY	FIREMEN'S COATS MADE OF	USE IN GLOVES VESTS
TENSILE STRENGTH PSI	HIGH 27000 FIBER	400,000 *2
DENSITY g/cm^3 (LB/in^3)	1.25 (.045)	1.44 (.052)
RESISTANCE TO WATER	GOOD	EXCELLENT
OIL/GREASE	GOOD	EXCELLENT
MILDEW	GOOD	———
COST *4	HIGH	HIGH

*1 KEVLAR 29 BROCHURE

*2 UNIMPREGNATED TWISTED YARN TEST–ASTM D2256

*3 IMPREGANTED STRAND TEST D2343

*4 MATERIALS ENGINEERING, Je '79, "COATED FABRICS

BLUNT BALLISTIC PROTECTION IN SOME SYSTEMS

GLASS	POLYESTER	NYLON POLYAMID
400 - 500F	350 *4	250 - 350F *4
NON-FLAMMABLE	LOI 20.6 (FABRIC) UL HB to VO	LOI 20.1 (FABRIC) FAIR CLASSV2
-100F *4	-100F	-100F
VERY LOW	14.5 *1	250 - 550
POOR	———	G
350,000 *3 SUSCEPTIBLE TO CREEP RUPTURE *1	HIGH, 162,500 *2 psi (YARN)	900 - 18000 psi
2.55 (.092)	1.38 - 1.41 (.050 - .051)	1.13 (.041)
EXCELLENT	EXCELLENT	GOOD
EXCELLENT	GOOD	GOOD
EXCELLENT	GOOD	GOOD
LOW	MODERATE	MODERATE

ON

Figure 2. Jacket Fibers

2

2.1.4 Coating Elastomers

Figure 3 gives the matrix for coating elastomers. Cost apart, the fluorocarbon elastomers look the best, having excellent flame resistance and high temperature operation. But chloroprenes can be formulated to have good properties for most requirements at a much lower cost according to Reference 4. The possibility exists that flammable materials such as nylon and polyester can be coated with a flame retardant elastomer which will overcome the flame susceptibility of the substrate fabric. That appears to be improbable, however, unless the weight of coating material is significantly more than that of the fabric. Then the coated fabric is likely to become too heavy. Therefore, it appears that nylon and polyester fabrics are less likely to serve acceptably in a jacket system than Kevlar or Nomex fabrics which are inherently flame retardant. The latter fabrics can, therefore, carry a lighter coating designed only to give the desired color and weatherability.

2.1.5 Films for Metalizing

Candidates for metalizing to create a highly reflective film to use in the reflective layers are shown in Figure 4.

Because of its flame resistance and high temperature performance, Kapton polyimide film is a good choice. It is also already available as a metalized film in thin gages (1/3 mil, 1/2 mil and 1 mil) as well as thicker films. If they are metalizible, fluorocarbon films appear otherwise to have good qualities and may avoid a

	HYPALON – DUPONT CHLOROSUFONATED POLYETHYLENE	CHLOROPRENE "NEOPRENE" – DUPONT
RESISTANCE TO HEAT	275F	225F
FLAMMABILITY	LOI 30 - 36	LOI 38 - 45
RESISTANCE TO COLD	-50F	-60F
ELONGATION	100 - 700	100 - 800
DENSITY gm/cm^3	1.11 - 1.28	1.23 - 1.25
RESISTANCE TO FLEX CRACKING	VERY GOOD	VERY GOOD
ABRASION	EXCELLENT	EXCELLENT
WEATHERING	VERY GOOD*[2]	VERY GOOD
WATER	GOOD	GOOD
ALIPHATIC HYDROCARBON	GOOD	GOOD
AROMATIC HYDROCARBON	FAIR	FAIR
HALOGENATED HYDROCARBON	POOR	POOR
ALCOHOL	GOOD	GOOD
COLORABILITY	EXCELLENT	FAIR

*[1] MATERIALS ENGINEERING, DEC. '79, PG 102,103

*[2] MATERIALS ENGINEERING, JUNE '79, " COATED FABRICS"

ETHYLENE/ACRYLIC	EPICHLOROHYDRIN	FLUOROCARBON
400F	325F	>550F
LOI 48*3	LOI 25 - 33	LOI 50 - 100
-30F	-15F to -80F	-50F
450	200 - 800	150 - 450
1.08 - 1.12	1.27 - 1.49	1.4 - 1.95
EXCELLENT	VERY GOOD	GOOD
EXCELLENT	FAIR GOOD	GOOD
EXCELLENT	EXCELLENT	EXCELLENT
EXCELLENT	GOOD	GOOD
GOOD	EXCELLENT	EXCELLENT
GOOD,	VERY GOOD	EXCELLENT
GOOD	GOOD	GOOD
FAIR	GOOD	FAIR GOOD
————	GOOD	VERY GOOD

*3 MINERIAL FILLED COMPOUNDS

*4 DESIGN NEWS 11-19-79 pg62

Figure 3. Coating Elastomers *1

2

	POLYESTER	"KEL-F"-3M "ACLAR"-ALLIED CTFE	"HALAR"-ALLIED ECTFE	"TEFZEL"-DUPONT ETFE
RESISTANCE TO HEAT ASTM 759	300F	400F	300F - 360F	300F - 360F
FLAMMABILITY UL 94–	LOI 20.6 (FABRIC) UL HB to VO	OI > 95 V - O (1/8" x 1/2")	LOI 60 UL 94 VO	LOI 30 UL 94 VO
RESISTANCE TO COLD ASTM 759	-100F	-400F	-80F	"CRYOGENIC" (P15)
ELONGATION	60 - 165	125	150 - 250	300
DENSITY gm/cm^3	1.38 - 1.41	2.13	1.66 - 1.68	1.7
RESISTANCE TO WATER	G	G	G	G
RESISTANCE TO OIL-GREASE	G	G	G	G
COST		\$9 - 25/LB	\$8 - 10/LB	\$8 - 10/LB

*[1] GUIDE TO PLASTICS '78, PROPERTY & SPECIFICATION CHARTS, MCGRAW-HILL, 1977, NY

*[2] MODERN PLASTICS ENCYCLOPEDIA '78 - '79 P 643

...ONT	FEP	"TEFLON"-DUPONT PTFE = TFE	"TEDLAR"-DUPONT PVF	PVF_2	POLYPROPYLENE	POLYIMIDE "KAPTON"-DUPONT
...F	440 - 525F	500F	220 - 250F	260F	270 - 300F	750F*2
	LOI 95 VO	LOI 95 VO	LOI 22.6	LOI 48.7 VO	LOI 17.5 HB	V-0*1
...(P15)	-425F	-130F -425F	-100F	-100F	POOR (0° F) FOR CAST FILM -60°F FOR BIAXIALLY ORIENTED FILM	-450F
	300	100 - 350	115 - 250	300 - 500	550-1000	70*2
	2.15	2.1 - 2.2	1.38 - 1.57	1.76	.902 - .907	1.42*2
	G	G	G	G	G	G
	G	G	G	G	G	G
	\$6.50 - 8/LB	\$3.75 - 5.25/LB	\$10.15/LB PER DUPONT PRICE LIST FOR TEDLAR		1.85/LB* - 30,000 TELCON DOWCHEM JUSTIN PHILLIP GRANVILLE, OH POOR ADHESION OF METALIZED LAYER WITH TIME (*PER PONCON HERCULES 11/13/79)	

Figure 4. Films for Metalizing

potential noise problem produced by movement of stiffer films like polyimide. The elongation property in the matrix gives some assessment of that. Polyester film's flammability is a probl[illegible]owever, due to the small mass of material per unit area which may be present in a given blanket design, it is possible that a flammable film will not adversely affect resistance to flame for the whole blanket composite. If so, then polyester film may be quite suitable and is readily available and relatively inexpensive. It is also available in a wide variety of thicknesses from 1/4 mil upward.

2.1.6 Separator Materials

Separator materials are evaluated in the Figure 5 matrix. What is desired is a very open material which holds apart the two reflective layers yet offers little solid conduction paths. Metal meshes are eliminated on the basis of solid conduction since thermal conductivities for metals are from 10 to 900 times greater than plastics. The spunbonded scrim polypropylene and the nylon netting do not offer potential for separation distance selection. Separation would have to be only the thickness of available products which are on the order of 3 to 6 mils (0.08-.16 mm). Since convection analysis showed that the separation can be up to 6 or 7 millimeters without onset of convection, other candidates were given consideration.

	RETICULATED POLYETHER FOAM	RETICULATED POLYETHER/URETHANE
RESISTANCE TO HEAT MAXIMUM CONTINUOUS USE TEMP.	225F *1	220F*2
FLAMMABILITY	NO FR GRADE AVAILABLE UL94-HF-2*4	FLAME RETARDANT
RESISTANCE TO COLD MINIMUM CONTINUOUS USE TEMP.	-60F	-50F
COMPRESSION SET RECOVERY	EST 100%	EST 100%
DENSITY	1.5 lb/ft^3	2 lb/ft^3
RESISTANCE WATER	GOOD (BETTER THAN POLYESTER	GOOD*2
OPENNESS–TRANSMISSION OF IR	1/16" @ 20ppi ≈ 40%	1/8" @ 10ppi ~ 40%
LOW ABRASIVENESS (TO REFLECTIVE FILM, LEAST BEST	EST GOOD	EST GOOD

*1 POLYESTER FOAM DEGRADES AT COMBINED HIGH TEMPERATURES AND HIGH HUMIDITY (EST LIFE @ 215F 6-12 MONTHS)

*2 POLYESTER URETHANE FOAM DEGRADES AT COMBINED HIGH TEMPERATURES AND HIGH HUMIDITY (EST LIFE @ 215F 70% R.H. is 3-6 MONTHS)

*3 IMPORTED FROM KARL FREUDENBERG CO., WEST GERMANY

*4 GUIDE TO PLASTIC '78 PROPERTY & SPECIFICATION CHARTS MCGRAW-HILL, NY, 1977

TED IETHANE	PELLON NO. 5010 SPUN-BONDED POLYPROPYLENE WEB *3	NYLON NETTING	METAL MESH	EXPANDED REFLECTIVE POLYESTER SHEET
*2	250F	200 - 400F	EST 1500F	~ 240F (116C)
RDANT	LOI 17	LOI 20.1	NONE	POOR
	———	-100F	-400F	-100F
0%	NOT COMPRESSIBLE	NOT COMPRESSIBLE	NOT COMPRESSIBLE	MAY CRUSH RECOVERS ~ 80%
	———	———	———	DEPENDS ON EXPANSION ABOUT .014 g/cm³
*2	GOOD	GOOD	EXCELLENT	GOOD
- 40%	EST 80 - 90%	EST 80%	EST 60%	~100% (DUE TO REFLECTIVE SURFACES)
D	EST GOOD	EST GOOD	EST FAIR	EST FAIR

FOAM
IGH

70%

CONDUCTIVITIES OF SOLID METAL ARE ABOUT 10 TO 900 TIMES THAT OF PLASTIC

Figure 5. Separator Materials

2

The reticulated foams in columns 1 and 2 may be a suitable choice although probably one with a flame retardant would be necessary. Manufacturers' literature states that a 10 pore per inch foam is the coarsest one available, so that would be the choice in the attempt to minimize material in the separator to reduce solid conduction. An additional feature of these foams is that they can be compressed and recover fully.

Yet another separator is the expanded polyester sheet in the last column of Figure 5. This is a designed separator made from metalized plastic sheet which is slit and expanded to create separation. Liabilities for this separator are poor flame resistance properties (if polyester is used) and potential damage in compression (creasing of the film). However, it is probably the lightest, most efficient separator from the thermal resistance standpoint of all those considered.

2.2 Theoretical Study

2.2.1 Method, R-factor

There are just four modes of heat transfer available for heat to move through an insulation: convection, gaseous conduction, solid conduction, and radiation. Theoretical analysis of insulation is for the purpose of understanding how heat is transferred so that these modes can be reduced -i.e., thermal resistance increased. In layered blanket constructions such as are the subject of this study, it is necessary to break down the possible layer components into segments to which a resistance (R-factor) can be assigned.

Then these R-factors can be added in the proper way to arrive at an overall R-factor for the composite blanket. R-factor is a convenient means to deal with insulation effectiveness by analogy to electrical resistance.

The Fourier equation for heat conduction in one dimension is just

$$q/A = k\Delta T/t \tag{1}$$

where: q/A = heat transfer per unit area, w/m^2
k = thermal conductivity, $w/(m°C)$
ΔT = temperature difference through a material, °C
t = material thickness, m

Thermal resistance, R, is defined in the equation

$$q/A = \Delta T/R \tag{2}$$

so that

$$R = t/k \tag{3}$$

For constructions for which a thermal conductivity has already been measured it is not necessary to examine the thermal processes in detail. It is sufficient to simply use the ratio t/k for R-factor.

Where this is not the case, such as for an air layer between two planes separated with a medium, thermal transfer processes must be considered in detail. It will be shown that convection can be eliminated by using air layers about 1/4 inch thick or less in blanket design. Then gaseous conduction, solid conduction, and radiation are considered to be parallel processes of transfer so that their corresponding thermal resistances (R-factors) may be added in parallel as in Figure 6.

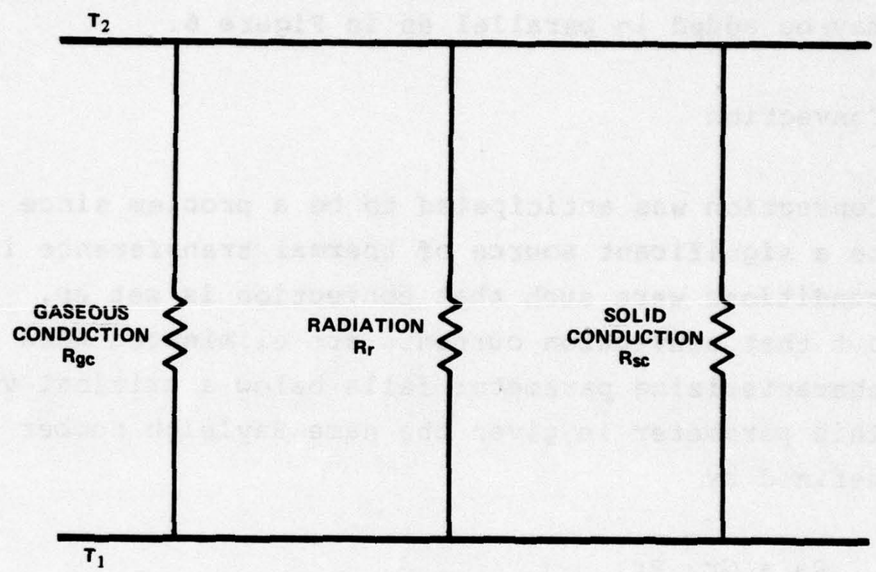
2.2.2 Convection

Convection was anticipated to be a problem since it could be a significant source of thermal transference if the conditions were such that convection is set up. It turns out that convection currents are eliminated when a characterizing parameter falls below a critical value. This parameter is given the name Rayleigh number (Ra) as defined by

$$Ra = Gr \cdot Pr, \tag{4}$$

the product of Grashof and Prandtl numbers. Grashof number is ordinarily used to characterize natural convection. Reference 1 gives an expression for Grashof number as

$$Gr = \frac{g\beta (T_1 - T_2)\delta^3}{\nu^2} \tag{5}$$



$$\frac{1}{R_{TOTAL}} = \frac{1}{R_{gc}} + \frac{1}{R_r} + \frac{1}{R_{sc}}$$

Figure 6. Thermal Resistances in an Air Layer with Plane Boundaries and a Separating Medium

where

g = acceleration of gravity, 9.806 m/s
β = temperature coefficient of thermal conductivity, 1/°K
T_1 = hot surface temperature, °C
T_2 = cold surface temperature, °C
δ = plate separation, m
ν = kinematic viscosity, m /s

Figure 7 shows the physical arrangement to which the definition of Gr applies, an enclosed vertical space. Horizontal enclosed spaces with the hotter surface on the bottom experience convection if the Rayleigh number exceeds about 1700 as indicated in Reference 1 (p. 256) and Reference 2 (p. 313). Reference 2 on page 316 suggests the limiting value 1700 for Raleigh number at which convection begins for vertical layers as well as horizontal layers heated from below. This work, therefore, assumes the value Ra = 1700 for all orientations of the insulating blanket as the limiting value for onset of convection.

Prandtl number is just the ratio of kinematic viscosity to thermal diffusivity

$$Pr = \frac{\nu}{\alpha} \tag{6}$$

It has the value for air of .71 at 300°K. For air, the temperature coefficient of thermal expansion, β, is simply expressible as reciprocal absolute temperature of the air, T,

$$\beta = 1/T \tag{7}$$

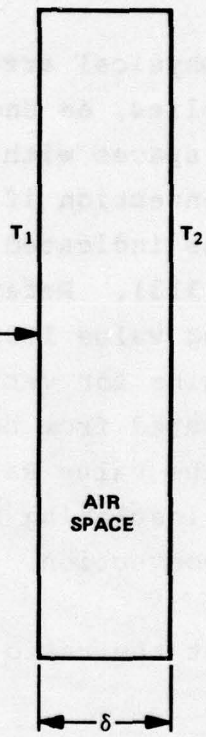


Figure 7. Heat Transfer Through an Enclosed Space

Combining these last equations (5, 6, and 7) with (4), the expression for Rayleigh number becomes

$$Ra = \frac{g\,(T_1 - T_2)\,\delta^3}{T\,\nu\alpha} \qquad (8)$$

In order to get an idea of the critical spacing at which convection will begin, it is necessary to make an assumption about the thermal gradient across a layer. The value 25°C per cm was selected (2500°C/m) as probably the maximum which is anticipated across a layer. The critical spacing δ_C can then be found with this assumption and the value of 1700 for Rayleigh number observing that $(T_1 - T_2) = (2500°C/m)\,\delta_C$ as

$$\delta_c = \sqrt[4]{\frac{1700}{g}\;\frac{T\,\nu\alpha}{2500°C/m}} \qquad (9)$$

$$\delta_c = 0.5131\,\sqrt[4]{T\,\nu\alpha\,\frac{sec^2}{°C}}$$

Equation (9) has been evaluated and graphed as a function of air temperature in Figure 8. It can be seen that the lower the temperature of the air layer, the thinner the critical thickness becomes for onset of convection. What must be selected then is the expected minimum average temperature for an insulating air layer in a blanket. If a value of about -10°F is picked (250°K), the graph shows that air layers thinner than 7 mm should not experience convection at this temperature and higher temperatures.

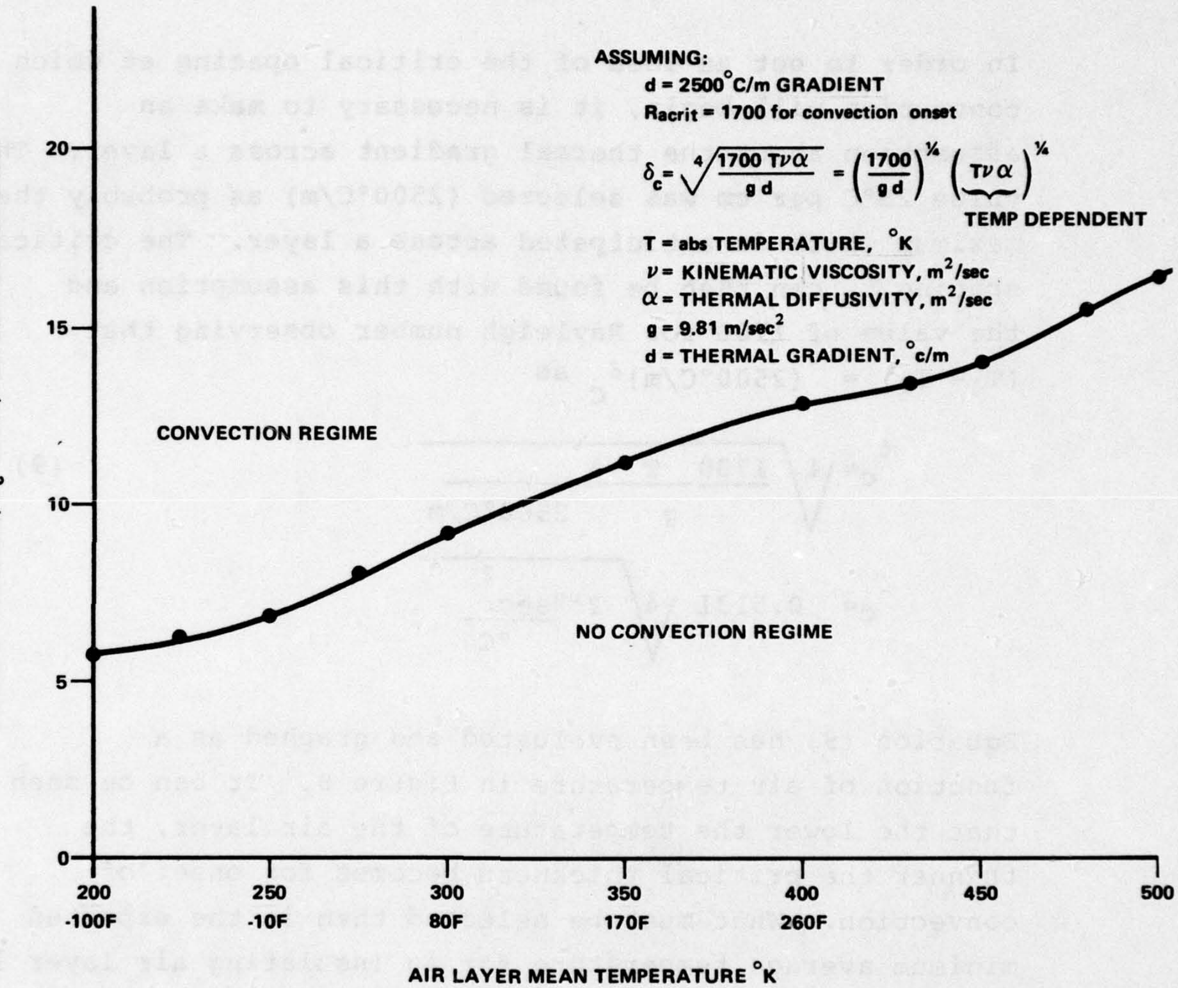


Figure 8. Critical Air Layer Thickness as a Function of Air Layer Mean Temperature

A 1/4 inch layer (6.35 mm), therefore, seems to be a suitable design maximum air layer thickness to avoid the effects of convection in a blanket.

Without convection as a significant mode of heat transfer within an insulation, there remains gaseous conduction, radiation, and solid conduction.

2.2.3 Gaseous Conduction Resistance

The gaseous conduction component of thermal resistance R_{gc} in an air layer is just the thickness to conductivity ratio as in (2) taking thermal conductivity from tables for air (Reference 1, p. 503 for example),

$$R_{gc} = t/k_{air} \tag{10}$$

where

t = air layer thickness, m

k_{air} = thermal conductivity of air, w/(m°c)

2.2.4 Radiation Resistance

Although radiation transfer is not a simple function of temperature difference ΔT, it has been treated similar to conduction using a resistance analogy as indicated by

$$q_r/A = \Delta E_b/Re \tag{11}$$

where:

q_r/A = radiation transfer per unit area

E_b = radiation potential, σT^4

R_e = radiation resistance based on radiation potential

σ = Stefan Boltzman constant, 5.67×10^{-8} $w/(m^2\ °K^4)$

T = surface temperature, °K

It is possible to relate R_e for radiation resistance (with ΔE_b as the current analog) to a radiation resistance or R-factor, R_r (with ΔT as the current analog) since

$$q_r/A = \Delta E_b/R_e = \Delta T/R \tag{12}$$

as

$$R_r = (\Delta T/\Delta E_b)\ R_e \tag{13}$$

This permits the direct use of work resulting in a radiation transfer resistance, R_e, from the references based on radiation potential as the current analog converting it to a compatible R-factor by multiplying by $\Delta T/\Delta E_b$.

Now since $\Delta T/\Delta E_b$ is not constant with temperature the value of this ratio should be determined at the average temperature in the insulating layer being considered. To simplify this calculation, a graph was prepared showing the variation of $\Delta T/\Delta E_b$ with average temperature. It is shown in Figure 9.

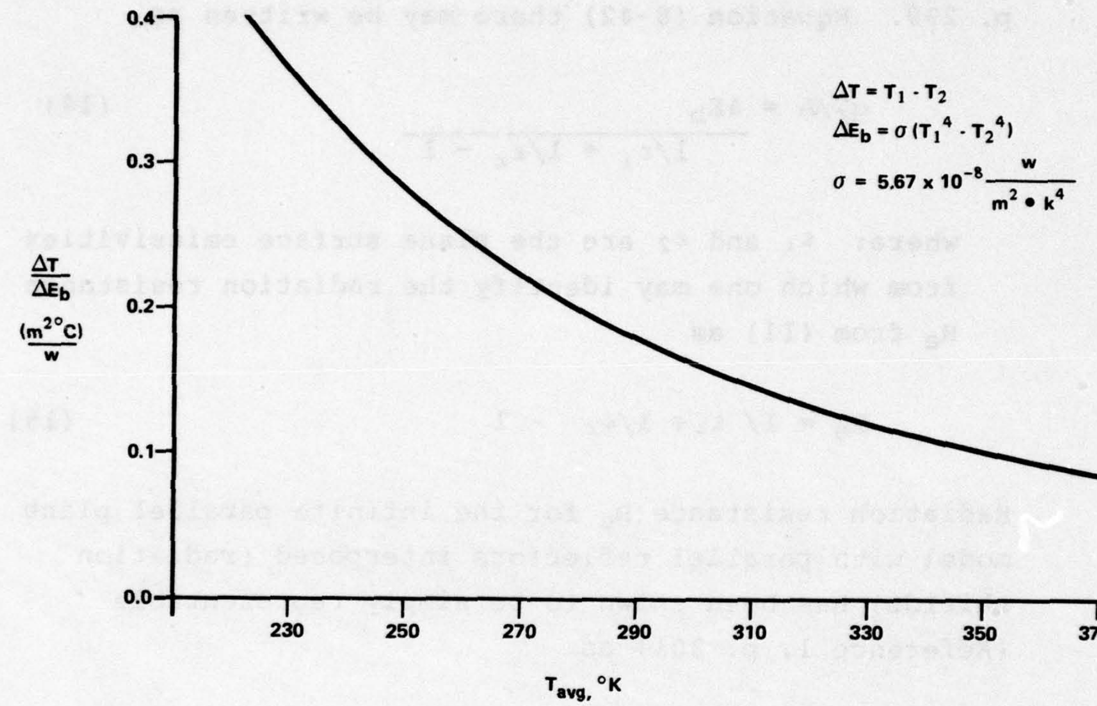


Figure 9. Variation of $\Delta T/\Delta E_b$ with Average Temperature

(U) This factor does not vary significantly with the range of ΔT values anticipated (from 5 to 30°C) so only variation with average temperature is depicted.

(U) A model available to simulate the layer structure in a blanket between two surfaces is two infinite parallel planes. That situation is dealt with in Reference 1 on p. 299. Equation (8-42) there may be written as

$$q_r/A = \frac{\Delta E_b}{1/\varepsilon_1 + 1/\varepsilon_2 - 1} \tag{14}$$

where: ε_1 and ε_2 are the plane surface emissivities from which one may identify the radiation resistance R_e from (11) as

$$R_e = 1/\varepsilon_1 + 1/\varepsilon_2 - 1 \tag{15}$$

(U) Radiation resistance R_e for the infinite parallel plane model with parallel reflectors interposed (radiation shields) has been shown to be simply representable (Reference 1, p. 301) as

$$R_e = (n + 1)\ (2/\varepsilon - 1) \tag{16}$$

where: n = the number of shields
ε = the emissivity for all surfaces (the same)

2.3 Blanket Design

2.3.1 Goals

As indicated in Attachment 1 to the contract, a basic goal of the study was to design blanket constructions which have an overall R-factor at least equal to that for a baseline blanket construction of three polypropylene foam layers (1/4 inch each) in a jacket. It was determined from material availability that making the R-factor just the same as the baseline blanket would not be possible for all designs. Therefore, it was decided to try for designs with the same or better R-factor. Flammability and flexibility were prime considerations. A matrix was used to place all designs side by side against the evaluating factors to help in the selection of designs for fabrication.

2.3.2 Layer Types

For the design analysis potential blanket constructions were assumed to be made up of combinations of three layer types:

1. Discrete insulation

2. An air layer with reflecting boundaries and a separating medium

3. A thin air layer

Discrete insulation refers to foams, felts and fiberglass for which thermal conductivities are given. The second layer type is the one requiring most analysis because there are no conductivities already on hand for them. It is the special area of attention of this report. The thin air layers are those which occur as layered constructions are put together in a loose assembly (such as between a foam layer and the jacket).

2.3.3 Factors for Layers

Table 1 presents a listing of R-factors for selected layer systems to use in blanket design. Material choices in it reflect conclusions from the material survey. As developed in Section 2.2, R-factor for discrete insulations is just the thickness divided by thermal conductivity for the insulating material, t/k. Values for k to determine R-factor are available in Figure 1, the material matrix for insulation. For Kevlar felt, however, the felt manufacturer has no k values yet. The fiber manufacturer states that Kevlar felt has about the same conductivity as fiberglass in the same bulk but will be just 60% as heavy due to the difference in densities between Kevlar and glass. Using this assumption, it was possible to generate the curve in Figure 10 for variation in Kevlar thermal conductivity with density. This curve suggests that the best weights of Kevlar to seek are less than 3 lb/ft and probably about 1 to 2 lb/ft to get low conductivity and lightest weight. Flexibility will also be improved with lighter felts. Values from the curve for different felt densities were used in computing R-factors for design with Kevlar felt.

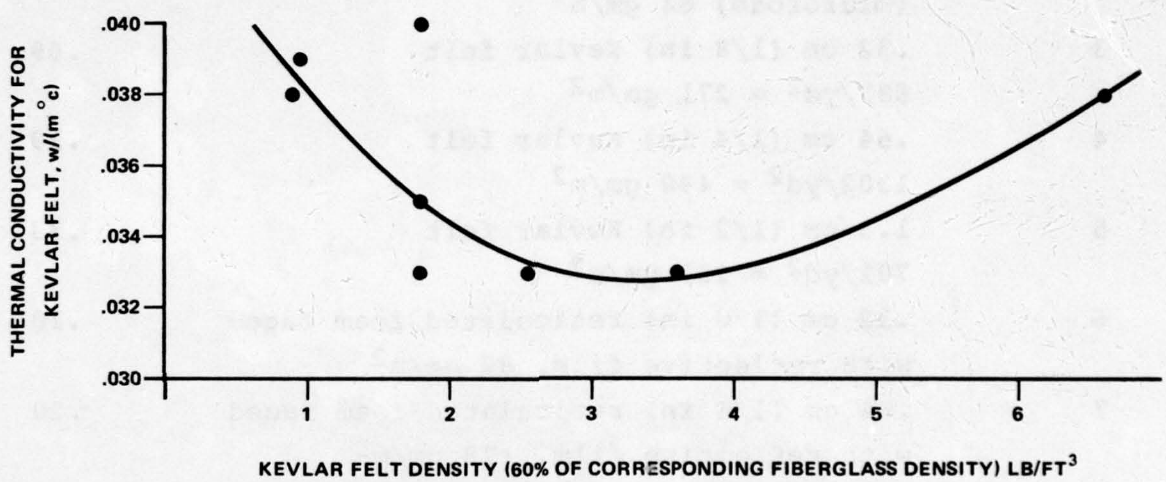


Figure 10. Estimated Thermal Conductivity for Kevlar Kelt vs Density

Table 1 R-factors for Materials and Layer Systems

Number	Material or Layer Description	R-factor $\frac{m^2 \circ C}{w}$
1	.64 cm (1/4 in) Pyrell polyester/urethane foam 2 pcf (203 gm/m^2)	.18
2	.76 cm (.3 in) polypropylene foam (microfoam) 84 gm/m^2	.195
3	.32 cm (1/8 in) Kevlar felt 8o2/yd^2 = 271 gm/m^2	.09
4	.64 cm (1/4 in) Kevlar felt 13o2/yd^2 = 440 gm/m^2	.19
5	1.3 cm (1/2 in) Kevlar felt 7o2/yd^2 = 237 gm/m^2	.33
6	.32 cm (1/8 in) reticulated foam faced with reflective film, 89 gm/m^2	.10
7	.64 cm (1/4 in) reticulated foam faced with reflective film, 178 gm/m^2	.20
8	.32 cm (1/8 in) expanded metalized film (2 mil) faced with metalized film	.117
9	.64 cm (1/4 in) expanded metalized film (5 mil) faced with metalized film	.226
10	1 cm (.39 in) expanded metalized film (5 mil) faced with metalized film	.35
11	.08 cm (.03 in) air gap faced with high emissivity materials	.026
12	.08 cm (.03 in) air gap faced one side with a high emissivity material, other side low emissivity	.029

Thin air gaps which may be expected to occur in a layered blanket between layers, also contribute to the overall thermal resistance. Equations (13) and (15) can be used for R-factor in this case, together with Figure 9 for the ratio T/E_b to determine the radiation resistance provided by the gap. Then gaseous conduction must be added as a parallel resistance to get the total resistance (Figure 6). It is estimated that an average gap in a layered construction would be about 0.03 inch (.8 mm) thick. This process was used to calculate the values for air layers (nos. 11 and 12) in Table 1.

The case of two reflective films and a reflective separator was treated by using equation (16) for radiation shields, assuming that the reflective separator constitutes a partial shield. Using the value $n = 0.3$ (for partial shielding) in (16) and $\varepsilon = .1$ yielded results for radiation resistance which were then added to resistance for air conduction to give the values for R-factor for expanded metalized film separating two reflective films (nos. 8-10 in Table 1).

A considerably more involved analysis was necessary to determine the R-factor for the type of layer formed by two reflective films separated by a layer of reticulated foam. This is presented in Appendix A. The development there accounts for solid conduction through the foam, air conduction, and radiation effects from the presence of the foam and for the reflective film surfaces.

Wherever necessary to determine temperatures for evaluating R-factors (the radiation resistance part), a thermal gradient of 25°C/cm was assumed.

2.3.4 Materials Used in Blanket Design

It may be noted that the R-factor for conduction through thin material such as the jacket cloth is negligibly small (like .005 m °C/w) so that the choice of jacket will have negligible influence on the R-factor for candidate designs. Therefore, in the design work on R-factor, no accounting of jacket material was made. Any choice of jacket with ordinary surface emissivities should produce the same blanket R-factor. What might be considered to improve R-factor slightly is use of a jacket fabric with the inside reflection.

Although it appears from the material survey that a Kevlar fabric coated with chloroprene would be an optimum jacket, it was necessary to use material on hand because chloroprene coated Kevlar is not a standard item with coaters making it and would be a developmental task. The cloth which was selected for service in the samples constructed under the contract is "Camouflage Cloth, Forest Green/Brown, Radar Scattering". This formulation is a woven nylon coated on both sides with flame retardant vinyl. It would be suitable for the blanket except for the temperature exposure anticipated (up to 250°F). Vinyl is probably not good over 175F (Reference 5, p. 786f).

For discrete insulation, three materials were used in designs: Kevlar felt, Pyrell polyester/urethane foam, and polypropylene foam. Metalized films used were mylar and polyimide partially because both of these are routinely metalized and available in thin gages. Separator materials used in designs were reticulated polyester/urethane foam and the designed expanded polyester film system described in Section 2.1.6.

2.3.5 Blanket Designs Matrix

From the building blocks provided by the listing in Table 1, different constructions of blankets were assembled. The baseline value for R-factor for the three 1/4 inch layers of polypropylene foam and jacket adds to 0.69 m °C/w. It was arrived at in a manner typical of all designs by adding values from Table 1: three layers of polypropylene foam (#2) and four air layers (#11) or (3 x .195 + 4 x 0.026) m °C/w = 0.69 m °C/w. Twelve candidate blanket designs are presented in Figure 11 with R-factors derived as above.

The value "$k_{apparent}$" in the blanket matrix is the thickness divided by the blanket R-factor. That gives an idea of the bulk efficiency of each design in restricting heat transfer. The lower the apparent conductivity, the better the bulk efficiency. A step further in evaluating designs is afforded roughly by the values of the number $1/(k_{apparent}\,\rho)$, for ρ as the area density for each design. That brings weight into the assessment. It should be observed that flammability and flexibility are not assessed with this factor and those characteristics must also be considered to select an optimum performing blanket. Cost considerations were not attempted at this time due to the experimental nature of the blanket materials. Ultimately that would also become a major factor.

	1	2	3
	½mil Py .64cm / X .64cm / Py .64cm	½mil Py .64 cm / RF .64cm / Py .64cm	½mil typ X .64cm / X .64cm / X .64cm
FLAMMABILITY	EST GOOD-BETTER WITH Kn in $\overline{X}$	EST GOOD BETTER WITH Kn in $\overline{X}$	EST FAIR-DEPENDENT ON JACKET UNLESS $\overline{X}$ MADE OF Kn
FLEXIBILITY	G	G	G
R FACTOR $\frac{m^2c}{w}$ **APPARENT CONDUCTIVITY** Kapp, $\frac{w}{m^\circ C}$	.70 .032	.67 .033	.74 .028
AREA DENSITY ρ (gm/m²/ without jacket with 7.50Z/yd² jacket (253 gm/m²)	531 1038	620 1126	338 844
UNCOMPRESSED THICKNESS, cm	2.23	2.23	2.06
MERIT FACTOR $\frac{1}{Kapp\rho}$, $\frac{m^3\ ^\circ C}{wkg}$	30	27	42
TEMPERATURE LIMITS	116°C (X MYLAR)	104C (RF)	116°C (X MYLAR)

SCALE: P = poor, F = fair , G = good

SYMBOLS: ____ **REFLECTING FILM** (½ mil and ¼ mil)
Kn = KAPTON FILM, METALIZED
Kv = KEVLAR FELT
Py = PYRELL POLYESTER/URETHANE
PP = POLYPROPYLENE FOAM
X= EXPANDED FILM SEPARATOR
RF= RETICULATED FOAM,10ppi "POLYCOUSTIC"

	4	5	6	7	8
m m m	½mil typ $\overline{X}$ 1cm $\overline{X}$ 1cm	½mil Kv .64cm RF .64cm Kv .64cm	½mil Kv 1.3cm X 1cm	½mil Kv .32cm X .64cm X .64cm Kv .32cm	½mil Kv .32cm RF .64cm RF .64cm Kv .32cm
NDENT S $\overline{X}$	EST FAIR-DEPENDENT ON JACKET UNLESS $\overline{X}$ MADE OF KAPTON	EST VERY GOOD	EST VERY GOOD	EST VERY GOOD	EST VERY GOOD
	G	F - G (DEPENDENT ON Kv DENSITY)	G	F - G (DEPENDENT ON Kv DENSITY)	F - G(DEPENDENT (Kv DENSITY)
	.75 .029	.69 .032	.74 .033	.74 .030	.69 .032
	231 737	1094 1600	362 868	773 1279	933 1439
	2.16	2.22	2.45	2.22	2.22
	47	20	35	26	22
R)	116°C (X MYLAR)	104°C (RF)	116°C (X MYLAR)	116°C (X MYLAR)	104°C (RF)

mil)

''

1

8	9	10	11	12	
.32cm .64cm .64cm .32cm	½mil PP .76 cm X .64 cm PP .76 cm	¼mil Kv RF RF RF .32cmtyp RF Kv	¼mil typ X X X X .32cmtyp X X	¼miltyp X X X .32cmtyp X X	BASELINE BLANK PP PP .64 cmtyp PP
Y GOOD	WITH PP PAINTED WITH INTUMESCENT PAINT EST GOOD – PAINT ADHESION IS QUESTIONABLE	EST VERY GOOD	EST FAIR-DEPENDENT ON JACKET UNLESS X MADE OF Kn	EST FAIR-DEPENDENT ON JACKET UNLESS X MADE OF Kn	
ENDENT ON TY)	G	F - G (DEPENDENT ON Kv DENSITY)	G	G	G
	.74 .034	.69 .032	.76 .027	.64 .028	.69 .038
	293 799	942 1448	278 784	233 739	252 758
	2.48	2.23	2.07	1.76	2.60
	37	22	47	48	35
	116° C (X MYLAR)	104°C (RF)	116°C (X MYLAR)	116°C (X MYLAR)	

47/48 blank

Figure 11. Blanket D

3

NE BLANKET

.64 cmtyp

ket Designs

4

2.3.6 Sample Blanket Construction

From the set of candidate blanket designs some were selected to build up in sample form for evaluation by MERADCOM. They do not represent the exact constructions recommended because it was not possible to procure all the desirable materials within the scope of this contract effort. The jacket supplied, for example, is not the optimum selection but is representative except for strength and resistance to heat of the recommended Kevlar/chloroprene jacket. It was used because it was available.

The set of samples supplied are indicated in Figure 12 using the same schematic representation as in Figure 11, the Blanket Designs Matrix, to denote different designs.

Symbols: Py = Pyrell; RF = Reticulated foam, 10 ppi; KV = Kevlar felt; Kn = Kapton film, reflective; My = Mylar film, reflective; X = Expanded reflective sheet; — = Reflective film

No.	Construction	Layers	Thickness	Sample Calculated R-Factor, °C m^2/w
No.(1).	Radar camouflage cloth jacket, 2 layers 1/4 inch polyester/urethane foam (Pyrell), 2 layers 1/2 mil metalized Kapton film, 2 layers 0.3 inch thick expanded metalized polyester film (5 mil), 1 layer	Py X Py	.64 cm .84 cm .64 cm	.77
No. 2.	Radar camouflage cloth jacket, 2 layers 1/4 inch polyester/urethane foam (Pyrell), 2 layers 10 ppi reticulated foam (Polycoustic) 1/4 inch thick, 1 layer 1/2 mil metalized Kapton film, 2 layers	Py RF Py	.64 cm .64 cm .64 cm	.67
No. 5.	Radar camouflage cloth jacket, 2 layers 1/4 inch thick Kevlar felt (Globe Albany XD-250N), 2 layers 1/2 mil metalized Kapton film, 2 layers 10 ppi reticulated foam (Polycoustic) 1/4 inch thick, 1 layer	Kv RF Kv	.64 cm .64 cm .64 cm	.69
No.(7).	Radar camouflage cloth jacket, 2 layers Kevlar felt (Globe Albany XD-250N) 1/4 inch, 2 layers 0.030 inch metalized Kapton film, three layers 0.30 inch thick expanded metalized polyester (5 mil) 2 layers	Kv X X Kv	.32 cm .84 cm .84 cm .32 cm	.89
No. 9.	Radar camouflage cloth jacket, 2 layers 1/4 inch polypropylene foam coated both sides with fire retardant paint, 2 layers 1/2 mil metalized Kapton film, 2 layers 0.3 inch thick expanded metalized polyester film (5 mil), 1 layer	PP X PP	.76 cm .84 cm .76 cm	.81
No. 10.	Radar camouflage cloth jacket, 2 layers Kevlar felt (Glove Albany 4581) 1/8 inch, 2 layers 1/4 mil metalized polyester film, 5 layers 10 ppi reticulated foam (Polycoustic) 1/8 inch thick, 4 layers	Kv RF RF RF RF Kv	.32 cm,typ	.69
No.(11)	Radar camouflage cloth jacket, 2 layers 1/4 mil metalized polyester film, 7 layers 3/16 inch thick expanded metalized polyester	X X X X X X	.47 cm,typ	.79
No. 14.	Radar camouflage cloth jacket, 2 layers 1/4 mil metalized polyester film, 2 layers Kevlar felt fluff H. Waterbury & Sons) 3/4 inch thick uncompressed, 1 layer	Kv	2.23 cm	.64
No. 15.	Radar camouflage cloth jacket, 2 layers 1/4 mil metalized polyester film, 3 layers Kevlar felt fluff (H. Waterbury & Sons) 3/4 inch thick uncompressed, 2 layers	Kv Kv	2.23 cm 2.23 cm	1.23

Note: Numbers for samples correspond to those in Figure 11 for blanket constructions. ( ) indicates "similar to" and underlined numbers are the same construction.

Figure 12. Sample Blanket Constructions

3.0 DISCUSSION

Although the R-factor of 0.69 $m^2{}^\circ C/w$ was used as a baseline value to aim at, it is not known if this value will be sufficient for effective thermal concealment against new thermal sensors. If the R-factor were greater, the effect would be a reduced influence upon the surface temperature of the blanket from the target object underneath and greater influence from the ambient environment. That is normally all to the good so that the greatest feasible R-factor is what is desired. Feasibility is controlled by such factors as weight and bulk which are related to the important factor of ease of use.

There is an instance in which strong influence from the ambient is detrimental. That is when the solar load elevates the surface temperature of camouflage material (such as this blanket) above natural background levels. Then the heated material becomes an unusual area of interest to observers using thermal imagers. However, that heating does not depend greatly on R-factor for blanket insulation, but rather on the solar absorptance of the exposed surfaces of the blanket and conditions of convection and radiation from the blanket which remove the solar load. Since that is not an object of this report and R-factor variation will not significantly affect surface temperatures due to solar load, no consideration beyond the present discussion has been given to this matter in this report. It is pointed out, however, as yet another factor to bear in mind for blanket design in a fuller sense.

One matter which should also be considered in blanket design evaluation is potential water absorption by fibrous material and open cell foams. It is not known just what

effect water absorption will have on blanket performance, but so long as water is present, some increase in thermal conductivity will occur. That degrades the insulating function of a blanket. Ref 7 (p. 112) suggests that insulation with water absorbed may have a conductivity four or more times published k values. A higher performance would be demanded for the jacket in preventing this from happening then for the designs which make use of materials which can absorb water to significant degree.

In this regard, it is noteable that the reflective layer design with expanded metalized polyester as separator would not absorb water and could offer good potential for draining off water which might gain entry to the blanket in which these layers were used. This easy drainage feature is pointed out in Ref 7 (p. 112) as significant for reflective insulation. However, all the materials which are presented in Fig. 11 (the blanket design matrix), can withstand a water soak and be restored to original condition by drying. It is just that during times in which the felts or foams are wet, blanket performance will be degraded.

It is interesting to observe in considering the reticulated foam separator that a 1/4 inch thick foam layer without reflective films on either side transmits about 20 to 25% of the heat which is expected to pass through the layer by radiation for anticipated temperatures of use. About 8% is solid conduction through the polyester/urethane webs, and the rest is conduction through still air (67 to 72%). This is the reason that placing reflective films on the sides of the foam layer can be expected to help. Increasing radiation resistance operates on a mode of transfer which is not insignificant. After placing reflective films on either side of the foam layer (1/4 inch thick) the relative proportions of heat

transmitted by each mode are then calculated to be 84% by air conduction, 10% by solid conduction and 6% by radiation. The overall thermal resistance increases from 0.16 $m^2{}^\circ C/w$ to 0.20$m^2{}^\circ C/w$ by this measure - about a 25% improvement.

4.0 CONCLUSIONS

As a result of the study on blanket insulation with reflective layers, it may be concluded that improved performance in blanket thermal resistance with decreased thickness should be possible through use of reflection layers. Probably the best blanket performers for high thermal resistance and low weight and thickness turned out to be insulating systems which are totally reflective-i.e. layers of reflecting film with reflecting separators.

It was found in theoretical study that convection can be suppressed in an air layer for an assumed temperature gradient of 25°C/cm if the thickness is maintained at about 6 mm or less, and the average air temperature is kept above -40°C between the surfaces. This led to a 1/4 inch maximum separation guideline in design of layered systems of reflectors (1/4 inch = 6.4 mm).

A promising material evaluated in the materials survey was Kevlar, both as a felt for discrete insulation and as a fabric for a blanket jacket system. It was concluded that a good jacket material would be 3.5 oz/yd Kevlar fabric coated to about 7 oz/yd (total weight including coating) with a fire retardant chloroprene elastomer. This jacket material should be non-flammable, strong, weather resistant and relatively lightweight. The felt is still close to the experimental stage but probably a 1-2 lb/ft Kevlar felt will be an optimum weight for Kevlar felt insulation. There is some possibility for blunt ballistic protection with Kevlar felt and jacket material.

For reflecting films for use in the reflecting layers metalized polyimide (Kapton) appears to be a good choice unless its inherent stiffness results in excessive noise for the assembly when moved as a blanket. There are, however, a number of other good candidate should Kapton prove undesirable. Kapton is one of the best in flame retardancy but there are others - notably fluorocarbon films which are also very good in flame resistance (LOI of 95).

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APPENDIX A (U)

R-factor for the Layer System Consisting of Two Metalized Films with a Polyester/Urethane Foam Separator

Solid Conduction in Reticulated Polyester Foam

Solid conduction must be considered in this case because an overall conductivity is not available which takes into account the resistance effect of reflecting film. Therefore, transfer processes must be examined in detail. What is in view for solid conduction is just the portion of heat which makes its way from one plane surface to the other by conduction through the solid fibers of the foam web - exclusive of conduction through the air surrounding the foam.

A factor which greatly simplified the process of determination of the solid conduction through a reticulated form was the discovery of an aluminum foam with the same structure as the reticulated plastic foam. It was thus possible with the counterpart in aluminum for the reticulated plastic foam to make comparisons of the measured thermal conductivities leading to conclusions about the solid conduction in the plastic foam.

Because of the inherent low emissivity of the aluminum material webs in the aluminum foam and the large number of webs interrupting transfer (acting as radiation shields), it was assumed that the proportion of heat tranferred through aluminum foam by radiation would be negligible compared to gaseous conduction and solid construction for aluminum foam.

This can be expressed as an overall conductivity being subdivided into two components - one for solid conduction and one for gaseous conduction,

$$k_{Al}\ \text{foam} = k_{sc}\ \text{Al foam} + k_{gc} \qquad (1)$$

Values for conductivities for the foam are supplied in manufacturers' literature for a 3% solid fraction ("volume percent") and gaseous conductivity is available from Ref 1, p. 503 for air. Then the solid conductivity for the aluminum foam can be found. Using values at 28°C, yields

$$k_{sc}\ \text{Al foam} = (3.46 \ - 0.263)\ \text{w/(m°C)}$$
$$= 3.43\ \text{w/(m°C)}$$

For the same foam geometry in plastic rather than aluminum, it can be assumed that the apparent solid conduction for the foam will be less than that for the aluminum foam in the proportion of the thermal conductivities for the solid components polyester versus aluminum in this case. Values are from Ref 3, p. 155

$$k_{polyester} = 1.1 \text{ to } 1.7\ \text{BTU in/(hr ft}^2\ \text{F)}$$

$$k_{Al\ 6061} = .52\ \text{cal/(s cm°C)} = 218\ \text{w/(m°C)}$$

Taking the average value for polyester, 1.4 BTU in/(hr ft^2 F) = ft^2 F) = 0.20 w/(m°C). The ratio of conductivities for polyester to aluminum is 9.17×10^{-4}. Therefore, the calculated solid conduction for the polyester foam with the same solid fraction (3%) is

$$k_{sc}\ pf = k_{sc}\ \text{Al foam}\ \frac{k_{polyester}}{k_{Al\ 6061}} \qquad (2)$$

$$= 3.43 \quad 9.17 \times 10^{-4} = 0.00315 \text{ w/ (m°C)}$$

Radiation Resistance for Reticulated Polyester Foam

(U) The value for overall conductivity for reticulated polyester foam without film facing, k_{rf}, is 0.27 BTU IN/(hr ft^2 F) from supplier literature, or in metric dimensions,

$$k_{rf} = 0.039 \text{ w/(m°C)}$$

This conductivity can be expressed as 3 apparent component conductivities

$$k_{rf} = k_{sc\ pf} + k_{gc} + k_r \qquad (3)$$

where:

$k_{sc\ pf}$ = solid conduction thermal conductivity for polyester foam, 0.00315 w/(m°C)

k_{gc} = thermal conductivity for air, w/(m°C)

k_r = thermal conductivity for radiation, w/(m°C)

(U) This allows determination of the radiation conductivity since all other terms are known. At 28°C k_{gc} = 0.0263 w/(m°C). Therefore

$$k_r = (0.039 - 0.00315 - 0.0263) \text{ w/(m°C)}$$

$$= 0.0095 \text{ w/(m°C)}$$

Now in trying to get a model of what this radiation resistance is

like in the reticulated foam it was considered that there is a surface resistance at the boundaries of a foam layer and another resistance in series with these surface resistances (R'_{ef}) as in Figure A1 through the foam itself. The surface resistances are associated with the bounding surfaces' emissivities as shown in Ref 1, p. 295. Total resistance in Figure 1 is just the sum

$$R_{ef} = (1-\varepsilon_1)/\varepsilon_1 + (1-\varepsilon_2)/\varepsilon_2 + R'_{ef} \qquad (4)$$

The relation between resistances based on radiation potential difference and temperature difference potential is $R_r = (\Delta T/\Delta E_b)R_{ef}$. This allows expressing R_{ef} using the value for k_r derived above as

$$R_{ef} = \frac{\Delta E_b}{\Delta T} R_r = \frac{\Delta E_b}{\Delta T} \frac{t}{k_r}$$

$$= (1-\varepsilon_1)/\varepsilon_1 + (1-\varepsilon_2)/\varepsilon_2 + R'_{ef} \qquad (5)$$

Solving for R'_{ef},

$$R'_{ef} = \frac{\Delta E_b}{\Delta T} \frac{t}{k_r} - (1-\varepsilon_1)/\varepsilon_1 - (1-\varepsilon_2)/\varepsilon_2 \qquad (6)$$

It is reasonable to assume that the surfaces used in measuring the overall thermal conductivity for the foam were high emissivity (low reflectance). Select 0.9 as a typical value. Select a thickness of 0.25 inch for the foam and use 28°C as the average temperature for the foam. Then (6) yields $R'_{ef} = 3.91$.

Now it is possible to calculate an effect for changing the surface layers to a reflecting layer film by evaluating the new surface resistances and then using the value just determined for the foam according to the model indicated in Figure A1.

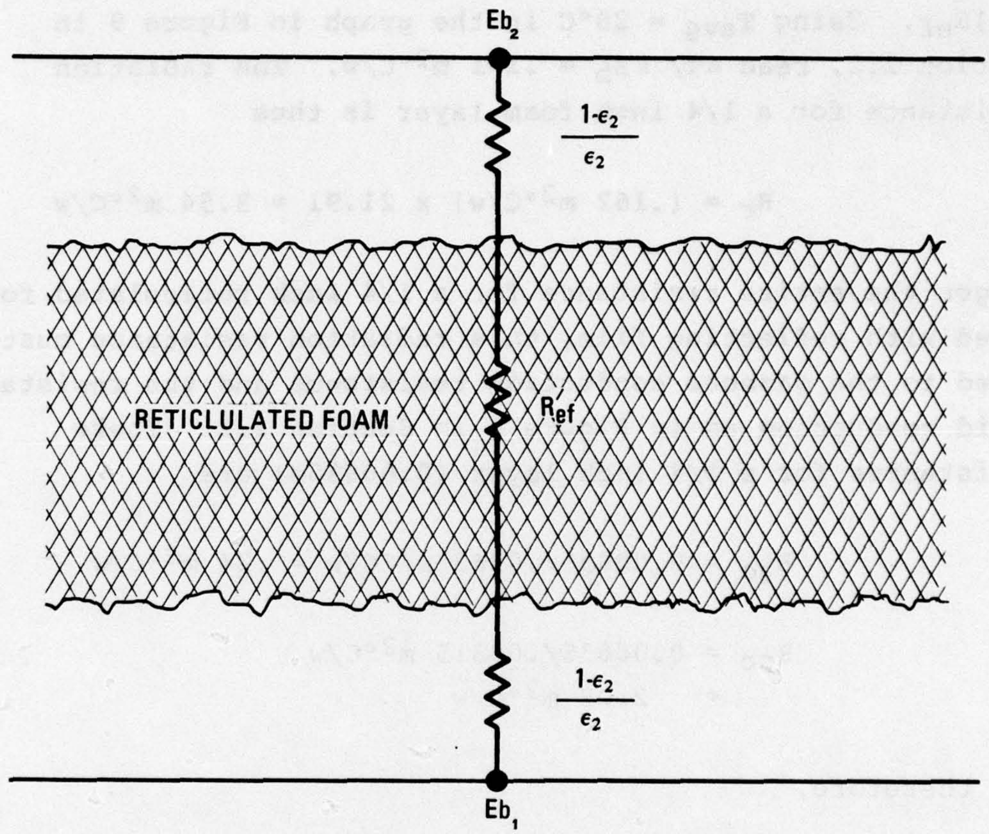

Figure A1. Radiation Resistance Model for Reticulated Foam using the Radiometric Potential Current Analog

(U) Assuming film emissivities of 0.1, the resultant resistance for radiation becomes, from (4)

$$R_{ef} = 2(1-.1)/.1 + 3.91 = 21.91$$

Converting to resistance (R-factor) based on ΔT, $R_r = (\Delta T/ \Delta E_b)R_{ef}$. Using $T_{avg} = 28°C$ in the graph in Figure 9 in Section 2.2, read $\Delta T/ \Delta E_b = .161\ m^2°C/w$. The radiation resistance for a 1/4 inch foam layer is thus

$$R_r = (.162\ m^2°C/w) \times 21.91 = 3.54\ m^2°C/w$$

(U) To get the entire resistance for a 1/4 inch reticulated foam faced with reflecting film, this radiation resistance must be added to the gaseous conduction resistance and the resistance for solid conduction as in Figure 6 in Section 2.2. These resistances for a 1/4 inch layer (0.00635m) are

$$R_{gc} = 0.00635/.0263\ m^2°C/w = .24\ m^2°C/w$$

$$\begin{aligned} R_{sc} &= 0.00635/.00315\ m^2°C/w \\ &= 2.02\ m^2°C/w \end{aligned}$$

and therefore,

$$R = \frac{1}{1/.24 + 1/2.02 + 1/3.54}\ m^2°C/w$$

$$= 0.20\ m^2°C/w$$

(U) It may be shown similarly that a 1/8th inch layer has an R-factor of $0.10\ m^2°C/w$.

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